

# Absorbed Dose and Dose Equivalent Calculations for Modeling Effective Dose

Andrew Welton\*  
USRP Intern  
NASA Johnson Space Center  
Mentor: Kerry Lee†  
Space Radiation Analysis Group  
SF2

While in orbit, Astronauts are exposed to a much higher dose of ionizing radiation than when on the ground. It is important to model how shielding designs on spacecraft reduce radiation effective dose pre-flight, and determine whether or not a danger to humans is presented. However, in order to calculate effective dose, dose equivalent calculations are needed. Dose equivalent takes into account an absorbed dose of radiation and the biological effectiveness of ionizing radiation. This is important in preventing long-term, stochastic radiation effects in humans spending time in space. Monte carlo simulations run with the particle transport code FLUKA, give absorbed and equivalent dose data for relevant shielding. The shielding geometry used in the dose calculations is a layered slab design, consisting of aluminum, polyethylene, and water. Water is used to simulate the soft tissues that compose the human body. The results obtained will provide information on how the shielding performs with many thicknesses of each material in the slab. This allows them to be directly applicable to modern spacecraft shielding geometries.

## Contents

<b>I</b>	<b>Introduction</b>	<b>2</b>
<b>II</b>	<b>Theory</b>	<b>2</b>
A	Biological Effects of Ionizing Radiation . . . . .	2
B	Vehicle Design and Shielding . . . . .	3
C	Location of Vitals . . . . .	3
<b>III</b>	<b>Computer Model Design</b>	<b>3</b>
A	Geometry . . . . .	3
B	Materials . . . . .	3
C	Detectors . . . . .	4
<b>IV</b>	<b>Methods</b>	<b>4</b>
A	Writing the FLUKA Input File . . . . .	4
B	Dose Equivalent Data Matrices . . . . .	5
<b>V</b>	<b>Results and Conclusions</b>	<b>5</b>
A	Error and Statistics . . . . .	6
B	Final Thoughts . . . . .	7

---

\*awelton1@gmail.com  
†kerry.t.lee@nasa.gov

## List of Figures

1	Shield Geometry Design . . . . .	4
2	Example of Dose vs. Depth in Water Plot, Thin Shielding . . . . .	5
3	Dose vs Depth up to 1cm of Water, Thin Shielding . . . . .	6
4	Dose vs Depth in Water, Thicker Shielding . . . . .	7

## I. Introduction

This paper describes work done from June-August 2010 using computer modeling tools to predict radiation dose and dose equivalent values. These quantities are relevant in calculating radiation effective dose, which is important in human spaceflight applications.

The current model used to predict dose and dose equivalent is a particle transport code called HZETRN.<sup>1</sup> It transports radiation, with a 1-D perspective, through a multi-element shielding slab of varying thickness. This is a very complicated physical process to model due to the difficulty of predicting secondary particles generated from radiation-shielding interactions. The radiation is then transported through a region of water with detectors placed at 25 different depths. The detectors take data such as particle type and fluence, linear energy transfer, dose, and dose equivalent. Water is used because it closely resembles human body tissue.

Due to the complexity of the modeling process just described, some assurance is needed that the results HZETRN produces are good. After all, humans will hopefully be occupying these vehicles, and we want our predictions to be reliable. One way of testing these results is to run the exact same simulation done with HZETRN with another transport code, in particular a Monte Carlo simulation. In this case the monte carlo simulation FLUKA<sup>2</sup> is known to be better because it includes more physics models, however it takes much longer to run. When comparing results from the two simulations, if they are very similar, it would be a good idea to use HZETRN results to calculate effective dose. This would reduce computing time greatly. If the results differ, and FLUKA is much better, then it should be used in the calculation.

My specific contribution to this project involved modifying a computer code written by Kerry Lee to write input files for FLUKA. The FLUKA input files are very long and tedious to write by hand. This code is very convenient, but it needed to be modified for this specific project. My contributions to the code are listed in the Methods section of this paper.

## II. Theory

The prediction of effective dose received, for a given spacecraft design, is a very complex process that involves many different variables. These variables take into account biological radiation effects, vehicle specific design and shielding properties, and location of vital organs within the vehicle. In this section I will briefly describe how each of these variables comes into play when calculating effective dose.

### A. Biological Effects of Ionizing Radiation

Ionizing radiation has different effects on biological cells. Some radiation has high enough linear energy transfer (LET) to completely kill a cell it interacts with. This is not very concerning due to our body's ability to get rid of the dead cell and make a new one. In large quantities, very high LET radiation is concerning due to its ability to kill massive amounts of cells at once; however, it is highly unlikely that a radiation event of that magnitude will occur in space. The most concerning is ionizing radiation with a LET capable of damaging a cell, but not killing it. This can cause the cell DNA to mutate, and begin reproducing as a cancer.

Two types of measurement used in the prediction of effective dose are: absorbed dose ( $D$ ) and dose equivalent ( $H_T$ ).<sup>3</sup> Absorbed dose measures the amount of total energy deposited into a given amount material, and dose equivalent relates absorbed dose in human tissue ( $T$ ) to the amount of biological damage caused by radiation ( $R$ ). This relation is determined by the weighting factor  $w_R$ , that characterizes type and energy of radiation. Dose equivalent is given by the following equation:<sup>3</sup>

$$H_T = w_R D_{T,R} \quad (1)$$

## B. Vehicle Design and Shielding

In the space environment, radiation threats do not always come from one direction. Therefore, in order to predict effective dose, the entire spacecraft geometry, structure, and all radiation shielding elements must be accounted for. This is accomplished by running a ray-tracing model through a computer aided design (CAD) model of the spacecraft. The ray-trace starts at a point within the spacecraft, and sends many rays outward in a spherical pattern. The rays represent how much material they pass through, and the type of material. This information can then be converted into an equivalent thickness of any relevant material, in this case Aluminum and polyethylene were used. For every ray, this thickness data gives information about how well the spacecraft is shielded from radiation in that particular direction. This is very useful when calculating effective dose.

## C. Location of Vitals

The final variable taken into account is the location and orientation of a human body within the spacecraft. This provides information about where vital organs are located, and how vulnerable they are to radiation within the vehicle. This is important because different organs have different dose limits, depending on their susceptibility to radiation.

Effective dose ( $E$ ) is the sum of all the weighted ( $H_T$ ) for all irradiated tissues and organs. This introduces a tissue weighting factor  $w_T$  that takes into account the sensitivity of organs to radiation damage. Effective dose is then given by the equation:<sup>3</sup>

$$E = \sum_T w_T H_T \quad (2)$$

## III. Computer Model Design

The particle transport code FLUKA is a good candidate for comparison with HZETRN. It's 3-D geometry structure is ideal, and it can support the shielding materials needed in the model. It can also output the proper data types needed for a good comparison. The next logical step is to build a geometry within FLUKA that matches the geometry modeled within HZETRN.

### A. Geometry

The Geometry design is relatively simple. Figure 1 is a visual representation of what the computer needs to model. It consists of a two element shielding slab defined within some boundary space, a region of water, a simple three part detector, and a beam source. The beam source used for this model follows the King solar particle event spectra.<sup>4</sup> This spectrum consists of protons with energies ranging from 1MeV to 1,200MeV.

In order for FLUKA to fully understand the geometry shown in Figure 1, it must be broken down and built in many pieces. This building process starts with geometric elements such as rectangular parallelepipeds (RPP) and X-Y planes (XYP). This skeletal structure is then divided into user defined regions. An example of a region (call it Region 1) is: In-Between XYP1 and XYP2, Inside RPP2. This definition process is repeated for every region within the geometry. Once the regions are defined, FLUKA needs to know what materials to assign to each region.

### B. Materials

Looking at Figure 1, one can see three distinct materials used in the model: aluminum, polyethylene, and water. FLUKA has knowledge of a number of elements, but one needs to combine these elements into materials in a way understood by FLUKA. Different elements can be combined to form any material without difficulty. The user has a choice to create new materials by giving FLUKA elemental mass fractions, or by defining the atom or molecule content of the material. Once the necessary materials are defined, they can be assigned to their proper regions.

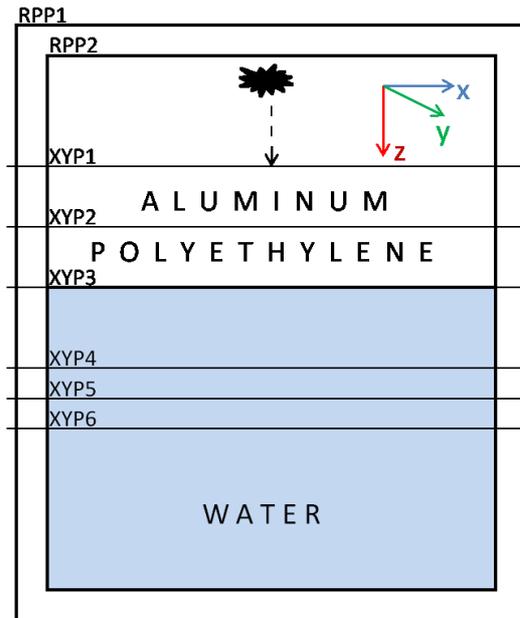


Figure 1. Shield Geometry Design

There are two other materials not shown in the figure that also need to be assigned: vacuum and black-hole. Black-hole is an imaginary material known to FLUKA that terminates all particles entering it. In the Figure 1 model case, black-hole would be assigned in the region between RPP1 and RPP2. This ensures that all particles are terminated there, and FLUKA does not try and keep track of them forever. Vacuum is exactly what it sounds like, and should be assigned, for this case, in the region containing the beam source.

### C. Detectors

The three part detector geometry is simple, and all that is necessary for the relevant quantities to be measured. Having three planes allows the detector to be divided into two regions. This is necessary for calculating Linear Energy Transfer(LET) for a particle passing through the detector. The center plane has another purpose besides acting as a regional divider. It also takes type and fluence data for each particle crossing its boundary.

FLUKA also follows all particle interactions that occur within the geometry. These interactions create showers of secondary particles that travel in all directions. Another advantage of having three plane, two region detectors is the ability to differentiate between forward and backward going particles.

## IV. Methods

### A. Writing the FLUKA Input File

To build the proper geometry in FLUKA a complicated input file must first be developed. This input file can be very long, and due to formatting very tedious to write. My mentor, Kerry Lee, developed a code in 2007 to write the input files for FLUKA. This code, called Slab, also submits the input file to FLUKA and graphs the data using ROOT.<sup>5</sup> Slab is very convenient; however, it needed to be modified in various ways. The primary modifications to Slab are listed in Table 1.

Additions to the Slab code were also necessary. These were added for organizational reasons, and to ensure efficient data production. The first of these additions allows the code to run on its own to collect data over a range of thicknesses supplied by the user. The second addition handles all FLUKA output data, and organizes it in a directory for each thickness combination. The output files and directories are all generically named. Therefore a legend file is also generated to display what thickness combination is placed in what directory. These additions were written in such a way that a cluster of machines can run from the same

**Table 1. Slab Code Modifications**

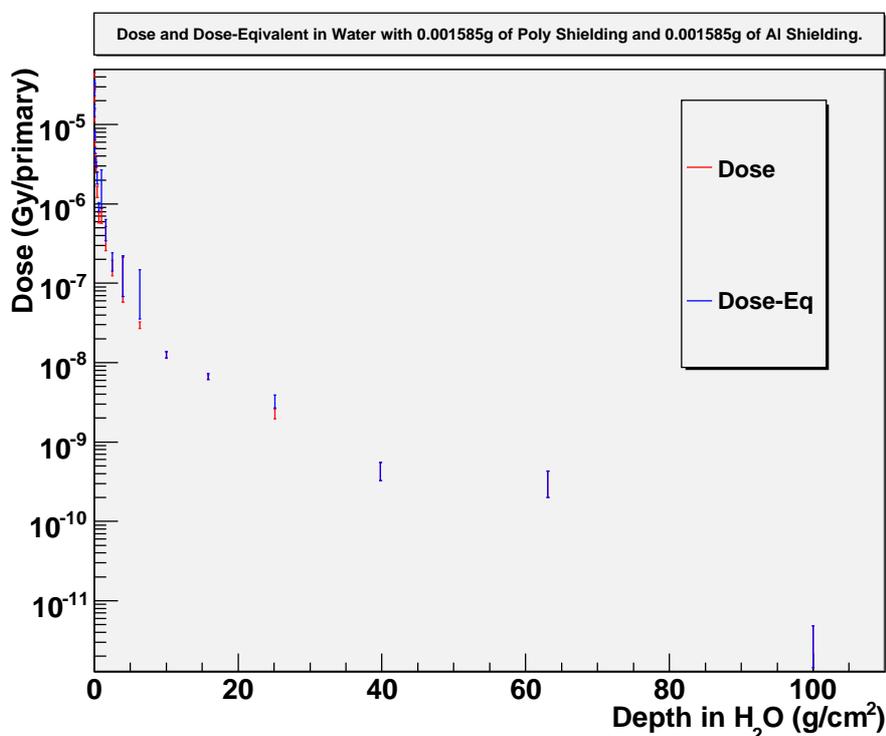
Previously Supported	Supported After Modification
One Shielding Slab	Two Shielding Slab
Al and Fe Shielding	Al and Polyethylene Shielding
One Thickness, One Slab	X Thicknesses for Two Slab Combination

working directory and not interfere with each other. That is, as long as the user follows the guidelines placed in the new README file.

### B. Dose Equivalent Data Matrices

The FLUKA executable is compiled with two FORTRAN routines named comscw.f and fkbirk.f. These routines are responsible for calculating Dose and Dose Equivalent from the FLUKA output data. Once this is done, the object containing the relevant dose and dose equivalent data can be read into an organized array. Ideally there is one array for each thickness combination run with FLUKA. This then allows for easy comparison with the HZETRN matrix.

## V. Results and Conclusions



**Figure 2. Example of Dose vs. Depth in Water Plot, Thin Shielding**

Overall the results from FLUKA were good. They contain reasonable data, and seem to provide sound dose and dose equivalent predictions. Figure 2 shows a Depth in Water vs. Dose/Dose Equivalent plot for every detector depth in water, for the shielding configuration with thicknesses of  $0.001585 \frac{g}{cm^2}$  of aluminum and  $0.001585 \frac{g}{cm^2}$  of polyethylene. Figure 3 contains data from this same configuration, but only for depths in water up to 1cm. One can see the degrading dose values as the depth in water increases. The statistical error is denoted by the +/- length from the center of the data bar.

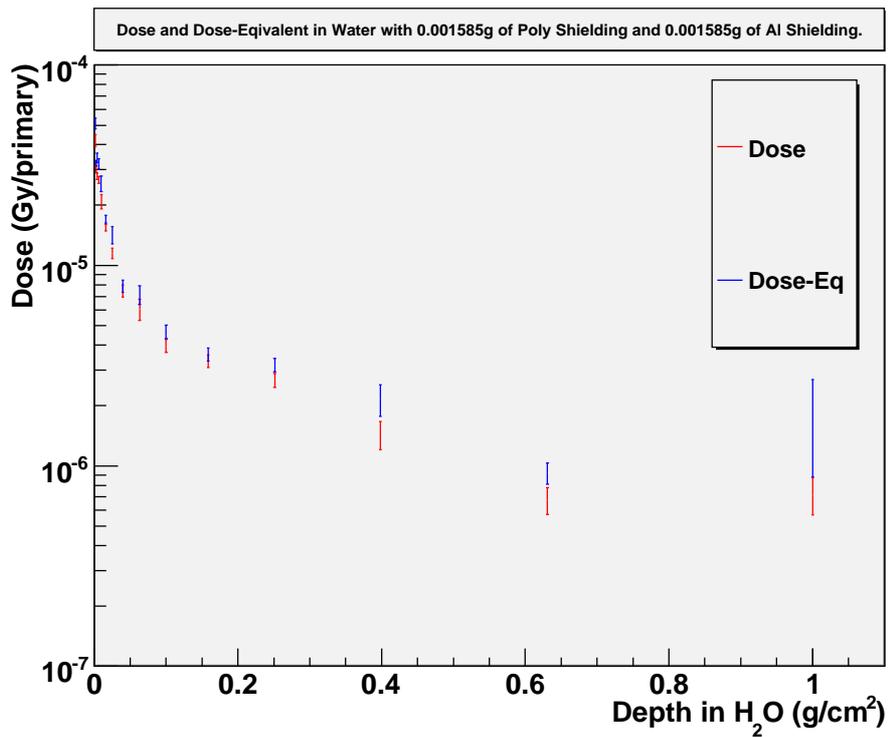


Figure 3. Dose vs Depth up to 1cm of Water, Thin Shielding

#### A. Error and Statistics

The error for this thickness combination is fairly good, however it could be better at a few instances. This is also the thinnest shielding combination, and statistical error should increase with the shielding thickness. This can be seen in Figure 4. For this data set, the beam source consisted of 5 runs with 15,000 particles per run. This takes approximately 45 minutes on a Pentium IV processor machine with 1GB of memory. Data is needed for 25 thickness of each shielding element. This amounts to 625 thickness combinations, with a total CPU-time close to 1month. Statistics could be improved by running with additional particles, however this will greatly increase run-time. If better statistics are needed, more computing power will be a necessity.

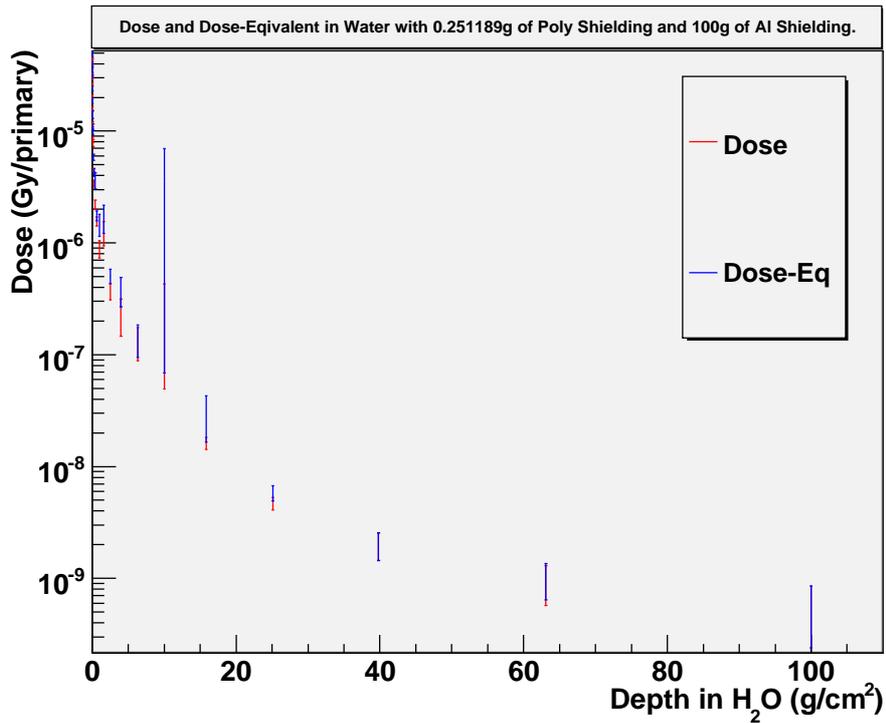


Figure 4. Dose vs Depth in Water, Thicker Shielding

## B. Final Thoughts

This project can be called a success for many reasons. First, all the objectives outlined in June between Kerry Lee and myself have been completed. The necessary modifications have been made to the slab code to accomplish the goal of taking data, comparable with HZETRN data, that can be used in the calculation of effective dose. A full run of 625 data sets has even been finished allowing for the verification of data. The only steps left to complete are to input the FLUKA data into a set of arrays, and compare them with HZETRN data.

Second, I have learned volumes during the process of this internship. I have excelled in learning about the C++ language, while still completing legitimate work. I have also experienced first hand the support provided by SRAG to the NASA human spaceflight program. Finally, I have gained more experience working with a team of scientists trying to accomplish many different tasks. This is probably the most valuable of all, and I will carry it with me through my career.

## VI. Bibliography

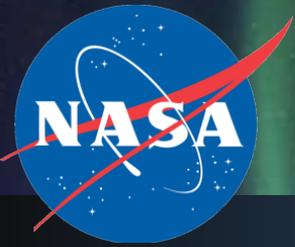
<sup>1</sup>Wilson, J. W., Chung, S. Y., Badavi, F. F., Townsend, L. W., and Lamkin, S. L., "HZETRN: A Heavy Ion/Nucleon Transport Code for Space Radiations," NASA Langley Research Center, 2003.

<sup>2</sup>Fasso, A., Ferrari, A., Ranft, J., and Sala, P., "FLUKA 2006," Copyright Italian National Institute for Nuclear Physics and European Organization for Nuclear Research.

<sup>3</sup>*Radiation Protection Guidance for Activities in Low-Earth Orbit*, National Council on Radiation Protection, 2000.

<sup>4</sup>King, J. H., "Solar Proton Fluences for 1977-1983 Space Missions," *J. Spacecraft*, 1974.

<sup>5</sup>Brun, R., Rademakers, F., Canal, P., Bellenot, B., Couet, O., Naumann, A., Ganis, G., Tadel, M., Moneta, L., Maline, D. G., Gheata, A., and Russo, P., "ROOT Ver. 5.16.00," 27 June 2007, <http://root.cern.ch>.



Andy Welton EXIT PRESENTATION

# EXIT PRESENTATION

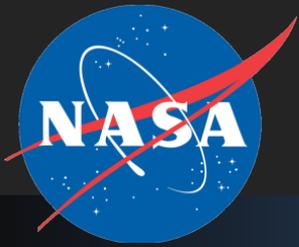
Andy Welton, SRAG-USRP Intern, Summer 2010



## EXIT PRESENTATION: Agenda

### Agenda:

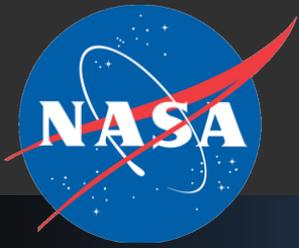
- Personal History
- Summer Project
- Skills Acquired
- JSC Intern Experience
- Personal Goals/My Future



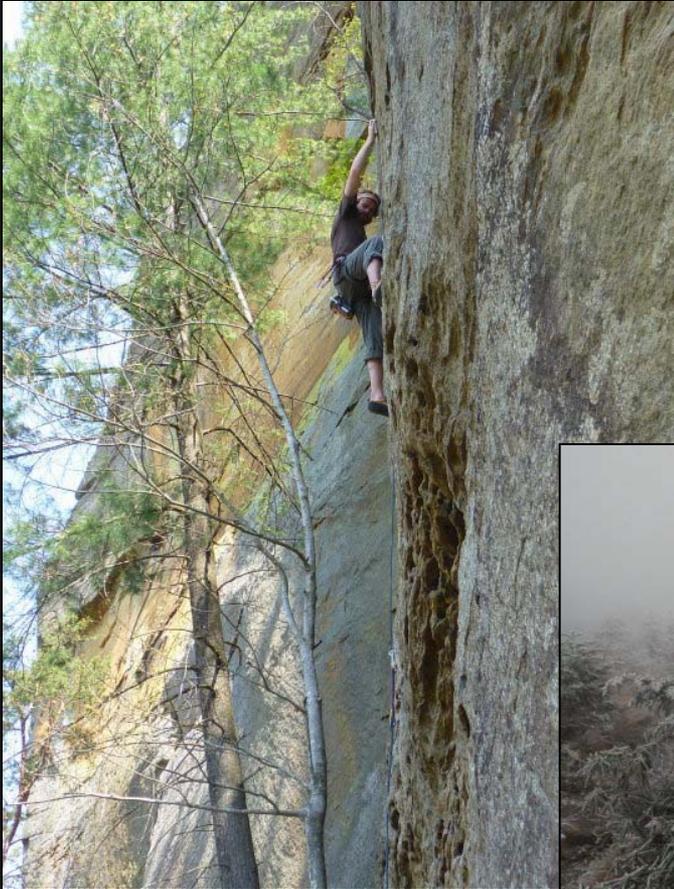
## EXIT PRESENTATION: Personal History



- Undergraduate Study at University of Tennessee, Knoxville
- MSGR Intern, NASA-MSFC, Summer 2009
- Graduated December 2009
  1. B.S. Physics
  2. Minor: Astronomy
- Decompression Period, Spring 2010
  1. New Orleans, LA
  2. Mexico City, MX
  3. Monterrey, MX
- USRP Intern, NASA-JSC, Summer 2010



## EXIT PRESENTATION: Hobbies





## EXIT PRESENTATION: Project Overview

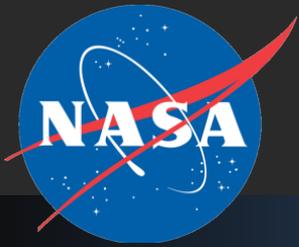
### Slab Calculations for Modeling Effective Dose

- Project Goals
- Background/Why is this significant?
- Process
- Results and Challenges
- Future Plans



## EXIT PRESENTATION: Project Goals

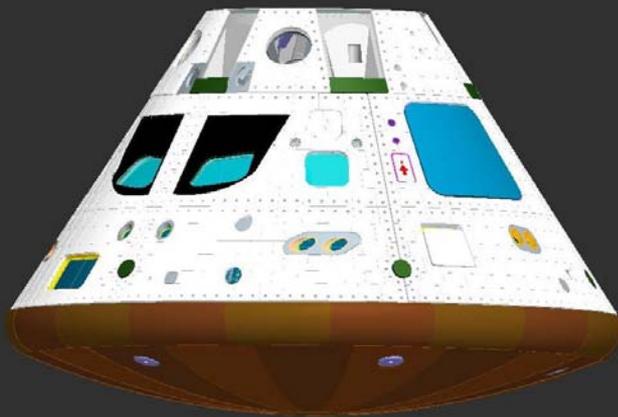
- Obtain absorbed and equivalent dose data
  1. Using FLUKA particle transport code
  2. Two material slab of Aluminum and Polyethylene shielding
  3. Many thickness combinations of each material
- Compare this data with similar HZETRN data
- Data eventually used to calculate Effective Dose
- Personal goals for the Summer
  1. Gain coding experience with C++
  2. Gain team oriented research experience
  3. Experience NASA operational support
  4. Have Fun!



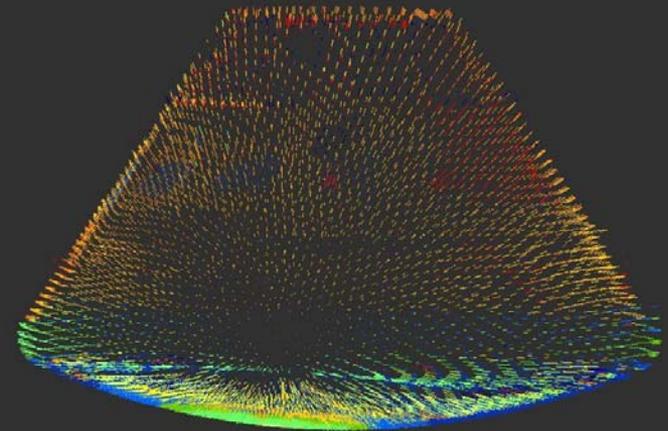
## EXIT PRESENTATION: Effective Dose

- Effective dose takes many things into account
  1. Amount/Location of shielding on a spacecraft
  2. Orientation of astronaut within spacecraft
  3. Sensitivity of Organs/Tissues to radiation

- Given by the equation: 
$$E = \sum_T w_T H_T$$



Orion Crew Module



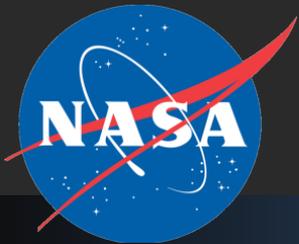
OCM Ray Trace



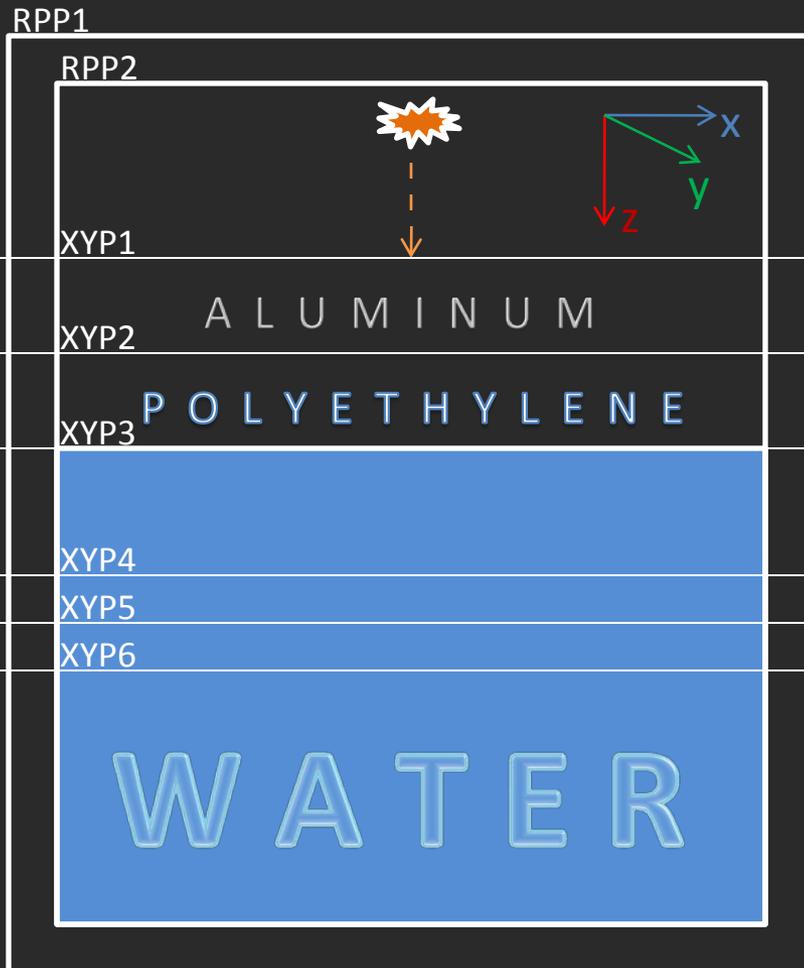
## EXIT PRESENTATION: Significance

- Absorbed dose and dose equivalent necessary to calculate effective dose
- Absorbed dose (D) measures total energy deposited in a given material
- Dose equivalent ( $H_T$ ) relates absorbed dose to biological damage

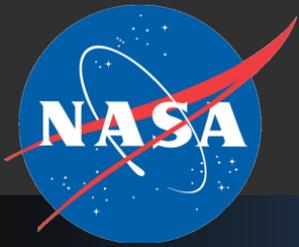
- Given by the equation: 
$$H_T = w_R D_{T,R}$$



## EXIT PRESENTATION: FLUKA Geometry

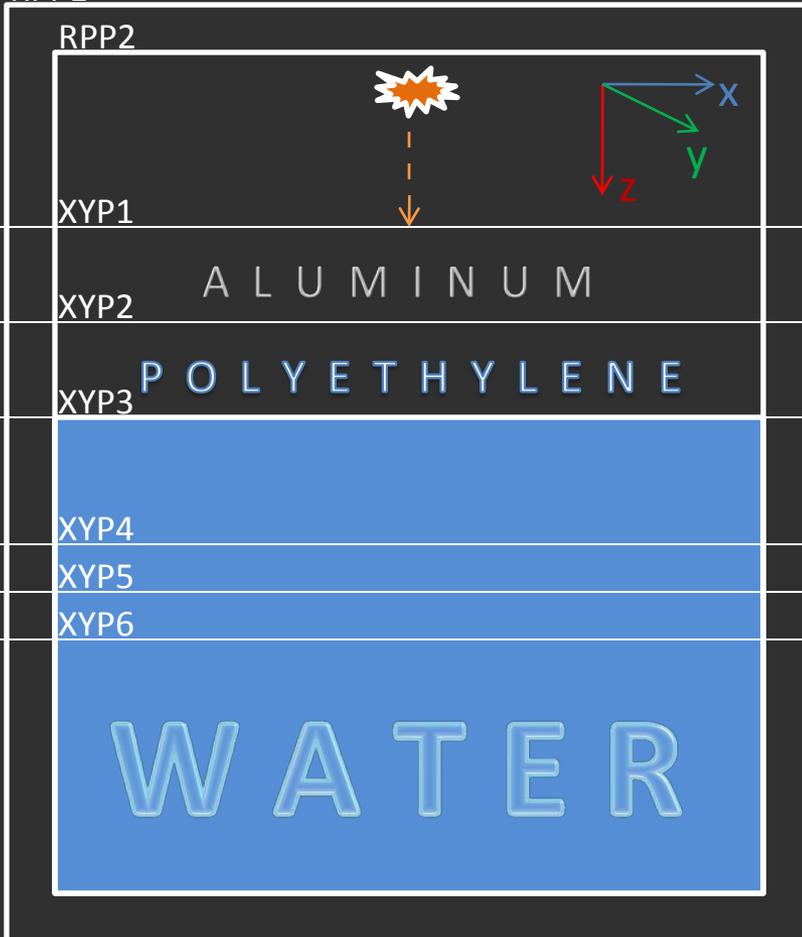


- Geometric elements
  1. Rectangular Parallelepiped (RPP)
  2. X-Y Plane (XYP)
- Vacuum and “Black Hole”
- Shielding regions
- Detector regions
- Water regions
- Beam position/orientation
- Scoring
  1. Particle Fluence
  2. LET Transfer
  3. Depth vs Dose and Dose Equivalent
  4. Forward and Backward

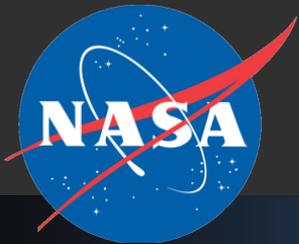


## EXIT PRESENTATION: FLUKA Geometry

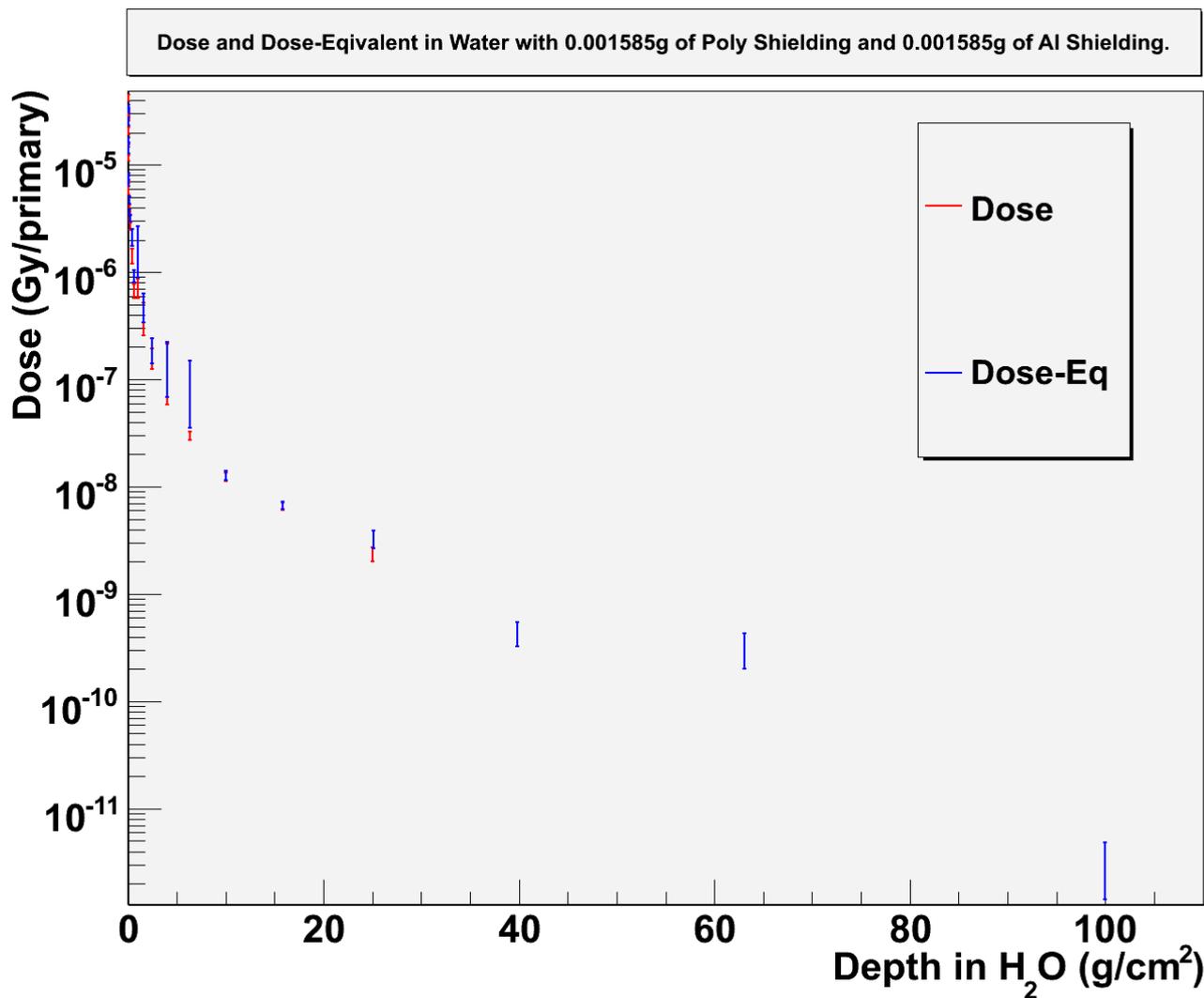
RPP1

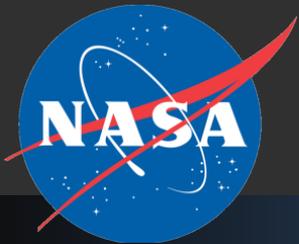


- Geometric scale
  1. 25,000m x 25,000m
- How to build this geometry?
- My contributions
  1. Two slab design
  2. Multiple thicknesses
  3. Code is self-sufficient
  4. Polyethylene

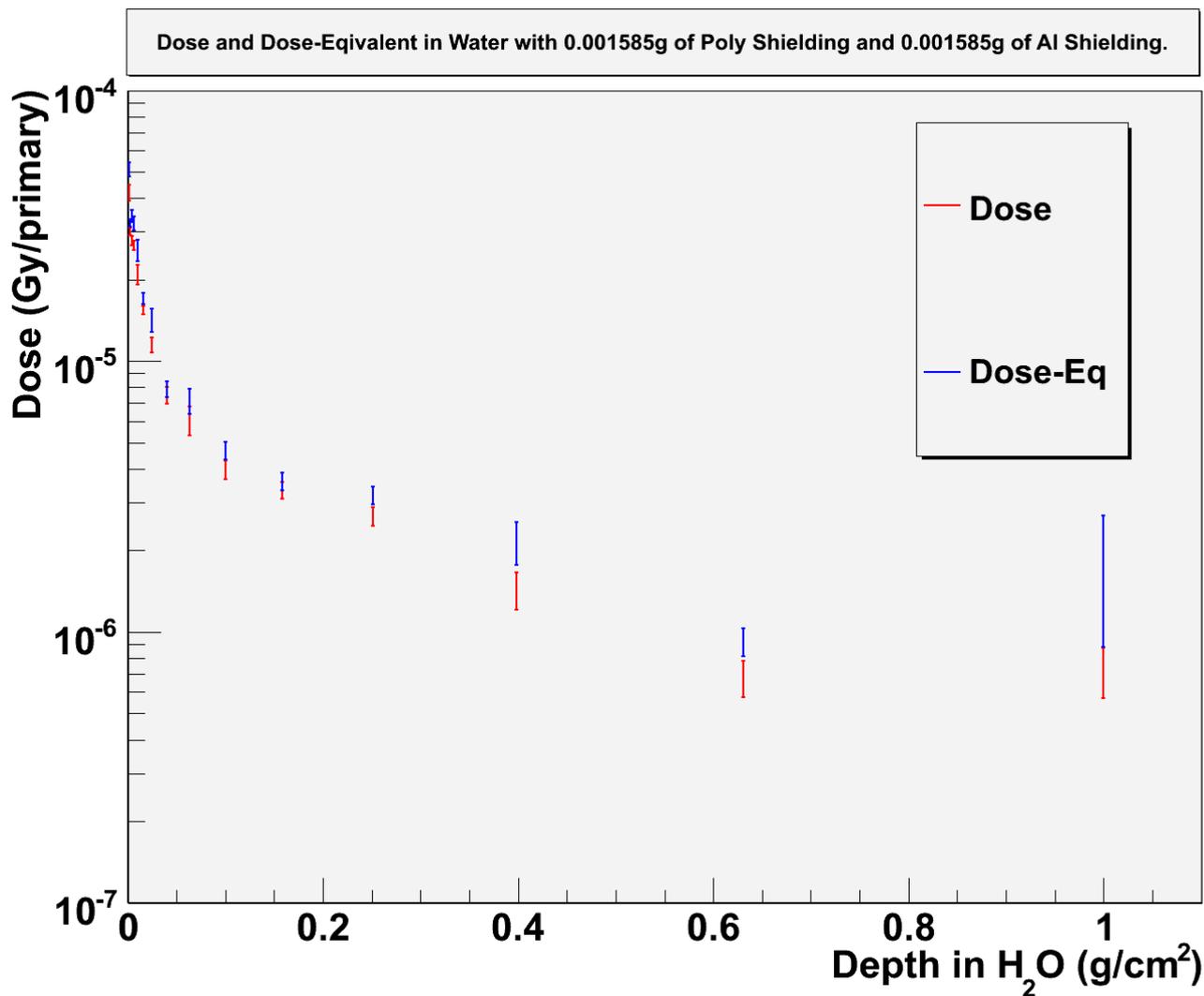


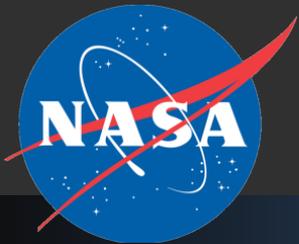
# EXIT PRESENTATION: Results



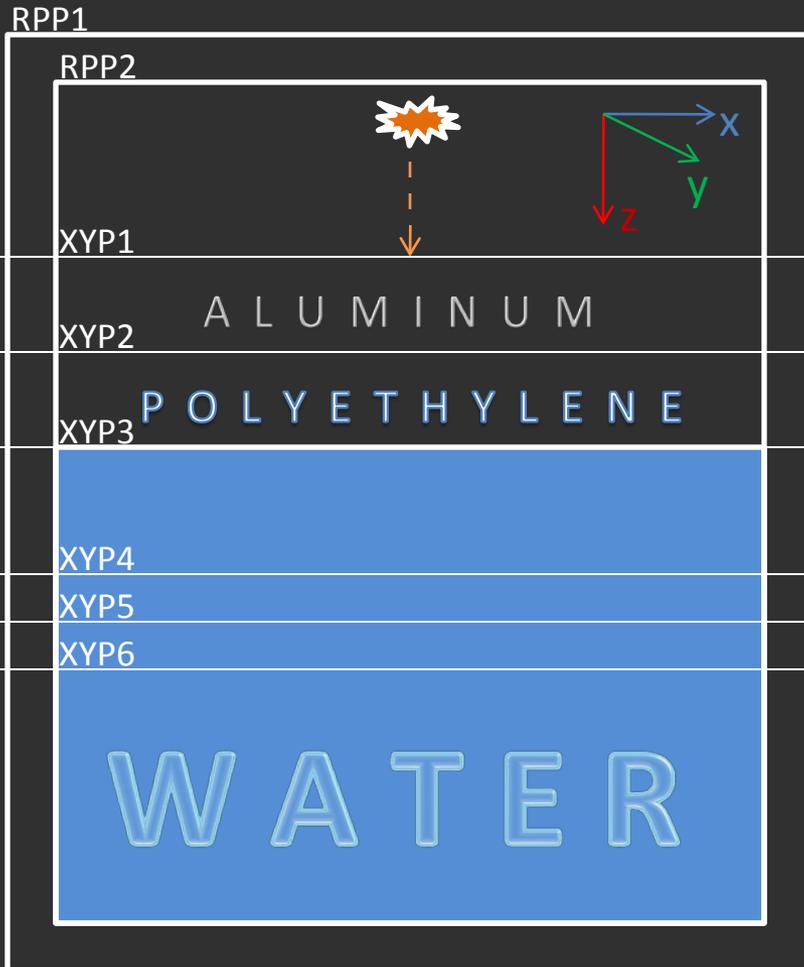


## EXIT PRESENTATION: Results





## EXIT PRESENTATION: Challenges/Future Work

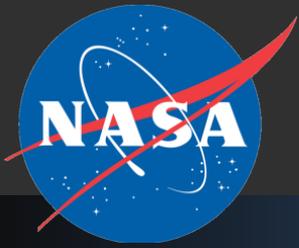


- Put data into matrix for comparison with HZETRN
- Implement FLUKA 2008 compatibility
- Run multiple iterations for improved statistics
- Run with FLUKA version modified by University of Houston



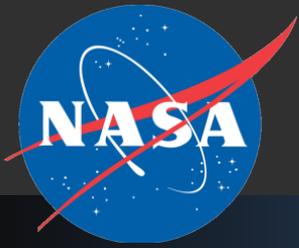
## EXIT PRESENTATION: Skills Acquired

- LINUX
- C++
- LaTeX document creation
- ROOT
- Expanded knowledge of space radiation analysis
- NASA mission operations
- Communication/Teamwork skills



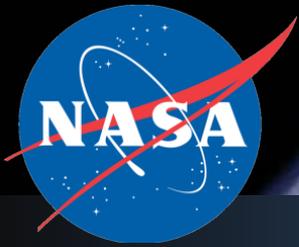
## EXIT PRESENTATION: JSC Intern Experience





## EXIT PRESENTATION: JSC Intern Experience





## EXIT PRESENTATION: Goals/Future

- Obtain a job with NASA and excel in my field
- Return to school for a Masters/Ph.D.
- Join the USA Astronaut Corps
- Utilize my achievements to inspire the next generation of space scientists
- Become fluent in Spanish
- Travel



EXIT PRESENTATION: Thank You!

- My intern coordinator Veronica Seyl
- The entire SRAG group
- Especially my mentor Kerry Lee
- Everyone who came out to this presentation